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Safety-based Maintenance for Geometry Restoration of Railway Turnout Systems in Various Operational Environments

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Abstract

Turnout system is one of the most critical infrastructures in the railway operations. As high demand in railway operation, the railway operators have to increase the axle load, traffic density and speed of the operation. These would be able to give high impact to the turnout system as increasing the vibration level and noise when the rolling stock crossing the turnout. Therefore, any failure in turnout system can cause negative impact to the operation in scope of maintenance cost and catastrophic consequence effect from the failure could happen such as major derailment. Safety-based maintenance (SBM) approach is an effective maintenance that takes safety into account in the maintenance by analysing the probability of the failure occurrence and severity of the consequence. Safety analysis is to ensure that the probabilities of the failure occurrence and the consequence from the failure such as death or injury and damage or loss of property can be minimised as to a level that is as low as reasonably practicable (ALARP). In this study, SBM and ALARP will be used to demonstrate the optimisation of geometry restoration activities of the railway turnout, which is essential for the safety requirements and quality standards. The failure behaviour in different operational environment such as effect of temperature, humidity, snow, dust, corrosive environment and natural calamity will be analysed to form fault tree analysis and establish a safety-based maintenance approach that is practical and useful for railway industry.

Keywords: Safety-based maintenance, Operation, Geometry, Railway turnouts, Risks, Failure modes, Probabilistic fault tree.

1. Introduction

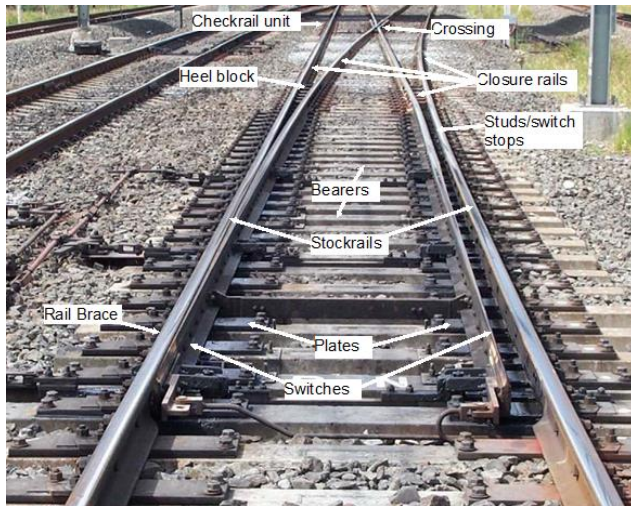
As an essential feature to enable rail operational flexibility, railway turnouts are special track systems used to divert a train from a particular direction or a particular track onto other directions or other tracks. It is a structural grillage system that assembles steel rails, points (or called 'switches'), crossings (or called 'frogs'), steel plates, rubber pads, insulators, fasteners, screw spikes, beam bearers (either timber, polymer, steel or concrete), ballast and formation, as shown in Fig. 1 [1]. There are two types of turnouts, a conventional turnout and a tangential turnout. Standard conventional turnouts are designed typically for straight main line track. The combination of switch length, heel angle and cross rate defines the turnout type, and they all typically have the same components. Tangential turnouts are defined by the radius of the turnout. Components in a tangential turnout vary as manufacturers place their own designs over the standard configuration. The traditional turnout structure generally imparts high impact forces on to its structural members because of its blunt geometry and mechanical connections between closure rails and switch rails (i.e. heel-block joints).

A railway turnout is a must-have structure in railway corridor whose crossing imparts a significant discontinuity in the rail running surface. High demand in railway operation, the railway operators have to increase the axle load, traffic density and speed of the operations (Kumar, 2008). The dynamic wheel/rail interaction on such imperfect contact transfer can cause detrimental impact loads on railway track and its components [1-4]. The transient vibration could also affect surrounding building structures. In addition, the large impact emits disturbing noises to railway neighbors [5]. The impact and ground-borne noises are additional to the normal rolling noise. Many previous studies have predicted impact forces and noise using numerical

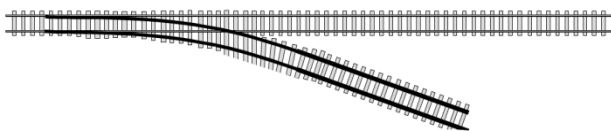
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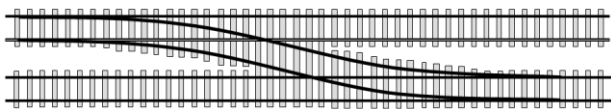
models [5]. However, only a few have implemented impact mitigation strategies in the field and even fewer field trial reports are available in the literature [5-13]. The impact mitigation strategies at an urban turnout include wheel/rail transverse profiling and longitudinal profiling of crossings, increased turnout resilience and damping, changes to rolling stocks, external noise/vibration controls, etc.



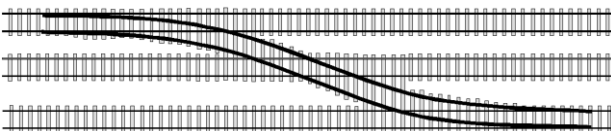
a) Typical components of a turnout



b) typical turnout structure



c) typical crossover structure



d) typical diamond structure

Fig.1.Special Trackwork Fundamentals

The secant design was early design were uncomplicated with only easy to manufacture components used. The improvement of the turnout had been done to produce improvement in wear on all parts of the turnout particularly at the switches as the design of tangential turnout. In tangential turnout, the switch curved tangential had been used to the straight stick rail. With tangential designs the switch entry angle of these tangents are significantly smaller than the angles in standard turnouts. This translates to less wear at the switch points and a reduction in turnout maintenance. Tangential turnouts generally incorporate asymmetric switches. By using this type of switch section the stock rail is able to be elastic

fastened on both sides. The disadvantage of using this section is that the heel end of the switch must be forged then flash butt welded to standard rail section. Much longer turnouts with larger radii and small crossing angles are required with particular attention paid to the design of switches and crossings. As traffic speeds increase, passenger comfort and safety become more critical. According to Kaewunruen et al. [19], the turnout consists of three major parts which are; set of switches (switch blades), common crossing and closure rail. All these three major parts are linked together and have significant functionality when train passing the turnout. It is crucial to ensure all these main parts work together without any failure. Electro-mechanic, hydraulic, and pneumatic are some types of the turnout systems. Turnout are manufacture in different weight such as 68kg, 60kg, 53kg, 50kg, 47kg, 41kg, 31kg & 22kg Rail.

Although a new method of geometrical design has been adopted for tangential turnouts, the transfer zone at a crossing nose in complex turnout system still imposes high-frequency forces to track components. Under static and high-intensity impact loading conditions, turnout geometry deteriorates at a higher rate than that of ordinary plan tracks [14-18]. These highly degradable geometry and components are due to many factors, such as:

- Extra length of timber bearers in comparison with standard sleepers
- Centrifugal forces through curved pairs of rails
- Forces and bending moments induced from points motors and other signalling equipment
- Impact forces induced by wheel-rail interaction
- Mechanical rail joints (maximum spacing of bearers is 600mm)
- Material properties of turnout components and support conditions
- Level of maintenance activities



Fig. 2: KTMB train derailed due to rail buckling and had landed on its side, trapping the driver and injuring about five passengers just before the Kempas, Johor station southern part of Malaysia.

At present, most modern turnout systems install concrete bearers/sleepers to improve track geometry quality and

durability performance of railway tracks. Track geometry quality is vital for public safety, as illustrated by Fig. 2. Train derailment could occur due to incorrect alignment or misalignment derived from poor lateral resistance. The emphasis of this study will be placed on the risk-based maintenance issues related to turnouts with particular focus on track geometry restoration. The life cycle risk analyses and failure analyses of the systems will be highlighted in this paper.

2. Failures and Fault Tree Analysis

Turnout is one of the high percentage of infrastructure component failure. According to the maintenance database, turnout contribute the largest reported track faults which requires high maintenance costs [16-27]. ORR [28] reported turnout failure is the highest failure from 2009 until 2014 compared to the others track related failure as shown in Fig. 3. Common damage mechanisms in turnout components are wearing, rolling contact fatigue and plastic deformation. Fig. 4 shows the example of the accidents due to turnout failure and consequence from the accidents.

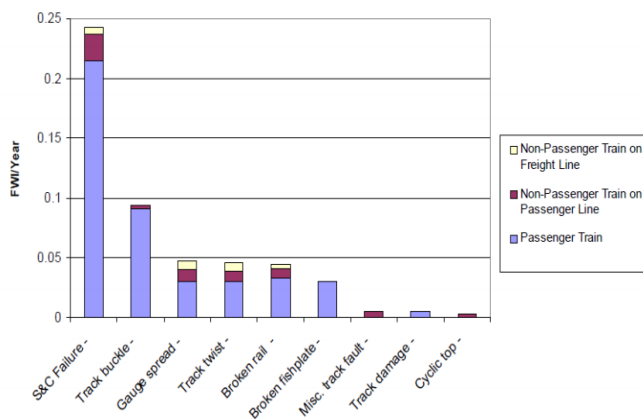


Fig. 3: Track system failure fatalities and weighted injuries (FWI)/year from 2009 to 2014 (Source: ORR, 2014)

Three main factors that contribute to the degradation and failure of the turnout components are train properties, track properties and also environment properties [29-30]. Below are the failure classification based on the components failure:

- Rail failure
- Sleeper failure
- Ballast failure
- Subgrade failure.

Below are the failure classification based on the nature of failure:

- Fatigue cracks failure
- Rolling contact fatigue cracks
- Wear failure
- Material deformation failure
- Shear failure

Both data in the Table 1 and Table 2 are based on the failure mode analysis (FMEA) that had been done for the UK railway in 2009 [20].

Table 1 The breakdown records of failure components in the UK railway [20]

Failed Components	Total Number	Frequency Distribution (%)
Switch rail	1113	45.3
Slide chair	747	30.4
Ballast	194	7.9
Schiwag Roller	138	5.6
Stretcher bar	111	4.5
Stock rail	71	2.9
Crossing	33	1.3
Fishplate	24	1.0
Back drive	18	0.7
Sleeper	5	0.2
Spacer block	4	0.2

Year	Country	Accident	Factor/Causes	Consequence	
				Killed	Injured
2013	France	Bretigny-sur-Orge derailment	Loose fishplate at crossing nose	6	>60
2012	UK	Edinburgh derailment	Switch rail worn-out	0	0
2007	UK	Grayrigg derailment	failure of the stretcher bars, incorrect setup of points and poor inspection procedures	1	88
2006	UK	London Waterloo derailment	Defective rail profiles and unlubricated switch blade profile	0	0
2002	UK	Potters Bar rail crash	Poor conditions of the 'backdrive' and others components	7	>70
1979	UK	Bushbury Junction	Camshaft of the diamond crossing failure	0	2
1946	UK	Lichfield rail crash	Point mechanism failure due to extreme cold weather	20	21

Fig. 4: Example of rail accident due to turnout failure

The failures also affects by the external factor such as the variation of the climate change and the geographical condition [29]. Table 3 below shows the relationship between weather and failure modes. It means that, the weather also play significant role in the contribution of failure. Hence, this external factor should take into consideration during conducting the risk assessment and risk analysis.

The studies about the wheel and rail impact (dynamic interaction) on the turnout also had been carried out to evaluate the impact force to the turnout which can be contribution of failure [18-19]. The irregularities on the wheel and rails will cause a large increase in the wheel/rail contact force, which may cause plastic deformations, wear and crack growth in the crossing also to the wheel. Worn wheels and/or geometric irregularities at the crossing, the wheel traction will be more uncontrolled, which cause a distinct impact load at the crossing nose. Other than that, if the level of the nose is

higher than the wing rail, this can contribute higher impact loading at the crossing. The high magnitude impact force is often transferred directly onto bearers and ballast with minimal energy dissipation (reportedly, often found with concrete, steel, composite bearers/sleepers). It then causes considerable deterioration and breakage of ballast, resulting in differential settlement at turnouts, especially at crossing panels [16-26].

Table 2 The number of potential failure mode for the turnout systems

Failure Modes	Total Number	Frequency Distribution (%)
Obstructed (Iced)	986	40.1
Dry chairs	441	17.9
Cracked/broken components	233	9.5
Voiding (ballast)	190	7.7
Out of adjustment	137	5.6
Contaminated (Leaves)	136	5.5
Plastic deformation/lipping	127	5.2
Wear	93	3.8
Loosed/missing(nuts)	89	3.6
Squat, RCF	8	0.3
Creep (switch)	8	0.3
Track gauge variation	7	0.3

3. Risk-based Maintenance (RBM) for Geometry Restoration

Risk-based maintenance (RBM) was introduced in the chemical engineering and petroleum refining field and expanding broad into others industrial fields. RBM is a tool for maintenance planning and decision making to reduce the probability of failure of equipment and the consequences of failure [22]. The probability of failure is the mean frequency or rate with which the specified failure event would be expected to occur in a given period of time, normally one year. The RBM is aimed to reduce the overall risk of the operating facilities as to achieve tolerable risk criteria [27]. Also, it is found that by using RBM, the prioritization in planning of maintenance will

only concentrated the truly need maintenance which consideration of adding factors such as cost and risk mitigation. With RBM, it can provide the rational basic of decision on making for life cycle maintenance planning. The RBM system comprises life cycle event trees, unreliability function analysis for field failure database and risk-cost analysis for various maintenance scenarios [23].

Table 3 Relationship between seasons and number of turnout failure in 2009 in the UK [20]

Seasons	Number of Failure Modes	Frequency Distribution (%)
Spring	421	17.1
Summer	427	17.4
Autumn	830	33.8
Winter	780	31.7
Total	2458	100

In order to determine the factors influencing the rail degradation process, various sources of information, including the current knowledge based on numerous theses and papers, as well as the theoretical and methodological contributions of various engineering books, have been examined. As seen in Fig. 5, the identified factors contributing to degradation are illustrated using a cause and effect diagram.

Thus, the identified factors influencing turnout geometry degradation, which essentially form the risk-based maintenance priority criteria and framework, are:

Age of Rails: there is a quadratic relation between time and degradation. In other words, the strength of rail falls along a parabolic path over a period of time and usage. After a period of use, replacement is required as aged material can adversely affect the materials interacting with it.

Axle load: it is clear that deterioration occurs quicker under heavy axle loads compared to light axle load (TRAC, 2001). This is claimed to be because of the high static and dynamic stress at the rail-wheel contact patch, which results in acceleration of rail degradation.

Ballast Cleaning: it is claimed that track structure may suffer from rapid degradation due to the non-homogeneity of the ballast beds. Hence, the track needs to be maintained, either by ballast cleaning or ballast renewal. Infrequent ballast cleaning is likely to cause undesirable changes in the track position, which results in more wear and more stress generation.

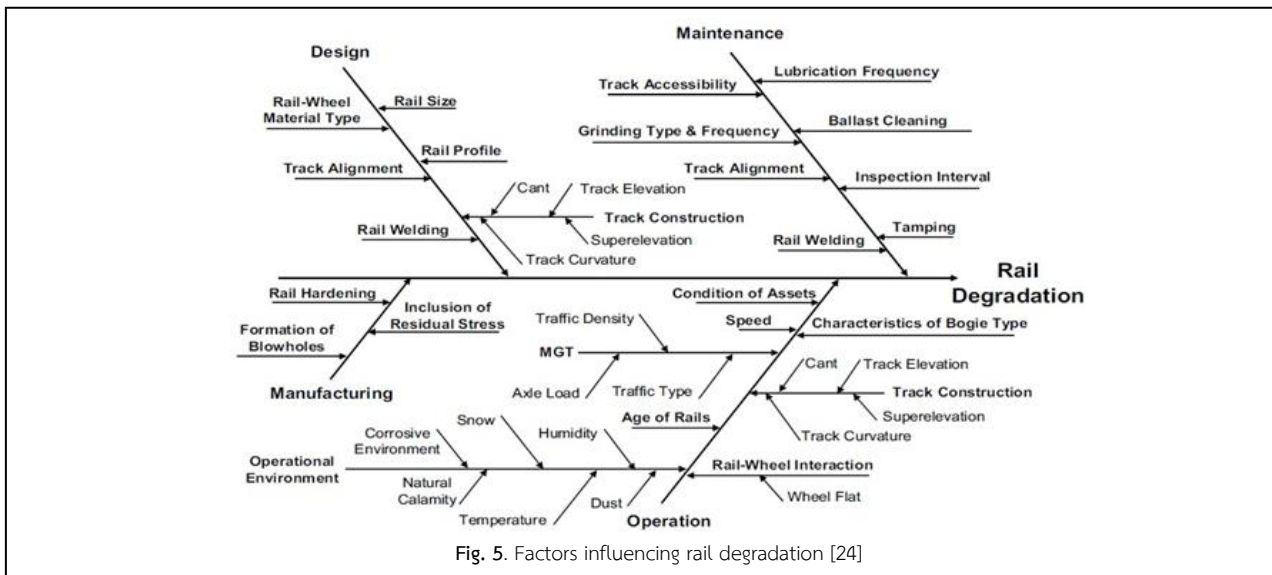


Fig. 5. Factors influencing rail degradation [24]

Characteristics of the Bogie Type: it is asserted that the characteristics of the bogie type may influence rail degradation. In the UK, large numbers of bogie types are present, but a few, namely Y25, NACO Swing Motion Bogie, Single Axle Leaf Spring, comprise 80% of all empty miles on the British network and almost 60% of the total loaded vehicle miles travelled on the network. Hence, this part of the research should be confined to these prevailing types of bogie.

Condition of other assets: as mentioned earlier, a switch works in tandem with other components, such as ballast, under sleeper pad, tie/sleeper, fastening systems and fishplate. In the event of these components being in poor condition, the degradation rate of the switch is accelerated.

Formation of Blowholes: there are a number of quality checks, such as ultrasonic inspection, before rails are commissioned. Hence, it is currently very rare to find blowholes or other manufacturing defects in rails, but this defect should be taken into account as well.

Rail Size: the thesis uses this term to express the weight of the rail in kilograms per metre. It is likely that rails of different sizes may have various degradation rates.

Grinding Frequency: grinding is essential in reducing the impact of rail defects and failures and extending rail life, as it prevents crack initiation and propagation of surface cracks (Reddy, et al., 2008). This could be a very important phenomenon in degradation, so it is emphasized that proper grinding, combined with lubrication, can extend the life span up to three times, whereas inappropriate application may considerably reduce it.

Inclusion of Residual Stress: during the heat treatment of a wheel, the rail welding process, or as a result of contact stresses generated by the wheels rolling on the rails, significant residual stresses are generated in the rail. Residual stress formation is highly likely to accelerate rail defect initiation and propagation.

Inspection Interval: a proper inspection involves prevention of system degradation.

Lubrication Frequency: aside from reducing noise and vibration at turnouts, lubrication helps to considerably decrease wear on rails and wheel flanges. Therefore, the method significantly increases the lifetime of switch tongues and stock rails due to deceleration of the rate of degradation.

Million Gross Tones(MGT): wear and fatigue, major contributors of rail degradation, also depend on Million Gross Tones (MGT). It has been found that estimation of parameters for failure models is performed accurately through expected number of rail defects over a period of time based on MGT of traffic, as failure is a function of usage in terms of MGT.

Operational Environment: environmental conditions, e.g. humidity, rain and snow, along with the presence of sand, have a very significant influence on the rate of degradation. For instance, the repetitive progress in the nature of trapped water in the cracks, melting and freezing, considerably enhances crack propagation. Moreover, in cold environment, there is expected to be an increase in track stiffness and the impact of track distortions on wheel-rail interaction forces. This gives rise to a substantial increase in wheel shelling damage. Additionally, a high ambient temperature might lead to track buckling as being responsible for the longitudinal expansion of rails, which poses a serious risk of derailment.

Rail Hardening: this is commonly used to increase the resistance to rolling contact fatigue of rails and reduce wear. The phenomenon also has an influence on degradation.

Rail Profile: different rail profiles are applied by different owners and manufactured using different design requirements. This presents different unique characteristics in degrading.

Rail Size: the review uses this term to express the weight of the rail in kilograms per metre. It is likely that rails of different size may have various degradation rates (Tzanakakis, 2013).

Rail Welding: as with the heat treatment of a wheel, residual stress also results from rail welding. The extent of weld-initiated residual stress can be decreased using improved welding technology and post-weld heat treatment.

Rail-Wheel Interaction: a recent study stresses that wheel-rail interaction at turnout generally results in deterioration of turnouts components due to detrimental dynamic responses arising from the non-smooth trajectory or wearing condition of crossing geometry.

Rail-Wheel Material Type: heat treatment is a significant phenomenon carried out on turnouts to increase the tensile strength and toughness of the rails. Various types of heat-treated steel rails are used throughout the world. Hence, the characteristics of different methods might play a significant role in influencing degradation.

Speed: the degradation rate may be accelerated with high train speed, as higher speed results in greater dynamic loading and, consequently, a faster rate of track degradation.

Super-elevation: the loading over high and low rails is usually different due to centrifugal force acting on the vehicle. For instance, if the speed is higher than the designed speed, the high rail is exposed to considerably higher forces, which results in greater degradation. Specifically, the force causes the wheel to make greater contact with the inner surface of the high rail than the inner surface of the low rail. In contrast, when the vehicle speed is lower than the designed speed, greater degradation will occur on the low rail.

Tamping: refers to a process by which the longitudinal and vertical alignment of the track is corrected by squeezing the ballast beneath the sleepers. A recent study shows that tamping has an effect on geometry deterioration.

Track Accessibility: where/when required, it is important that a maintenance team be on site. Otherwise, delay is inevitable, which causes acceleration in the rate of degradation, because its function is parabolic, as described previously.

Track Construction: a track is constructed in accordance with the required service lifetime, the requirements of the axle load, the amount of maintenance to be done, availability of basic materials and operating conditions. Like other infrastructure demanding huge amount of investment in the construction phase, maintenance plays a significant role in long-term cost effectiveness, and faulty applications give rise to huge loss. As such, it is important for the track to be constructed or reconstructed by an experienced subcontractor and contractor.

Track Curvature: the characteristic of the turnout curvature has a slight influence on degradation, as wear and plastic deformation vary with type. To be clear, tangent track implies fatigue, while narrow curve implies wear.

Table 4: Classification and phases of risk-based maintenance for railway turnout systems

Classification	Approach	Criticality
Hazard identification	Accidental scenario, stress-testing, event tree	Safety or Operational Risk
Consequence prediction	Source model, impact analysis	Vulnerability of systems and interdependencies
Likelihood estimation	Fault tree analysis, expert opinion	Frequency of failure occurrence
Risk assessment	Risk matrix, fuzzy logic, probability of failure	Common unit to communicate level of risk and urgency to respond
Risk acceptance	ALARP (as low as reasonably possible), other acceptant criteria	Rationale and judgement for decision making process
Residual risk monitoring	Inspections, remote monitoring, on-board inspection	Confidence level that enable certain risk taking with conscience
Maintenance planning	Reverse fault analysis, track quality analysis	Predictive, preventative, or corrective activities
Recovery and contingency planning	Uncertainty analysis and quantification	Level of uncertainty for contingency planning

Track Gradient: not only rail, but also the other component degradation, e.g. sleepers, is highly dependent on how inclined up or down the track direction is. This is because the system is also exposed to gravitational force.

Traffic Density: frequently used railways are highly likely to suffer from wear and RCF generation due to more rail-wheel interaction.

Traffic Type: heavily used railways, such as heavy ore lines on which a huge amount of materials is carried, could result in a more rapid degradation rate than clear lines.

4. Operational and Safety Risks

The approaches for risk-based maintenance methodologies are identified on the basis of the hazard identification, consequence prediction, likelihood estimation, risk assessment, risk acceptance, residual risk monitoring, maintenance planning, recovery and contingency planning, which is shown in Table 4. Based on these criteria, turnout maintenance can then be prioritized by such risks as demonstrated in Table 5.

Table 5: Maintenance priority for railway turnout systems (H: High; M: Medium; L: Low).

Failure Modes	Operational Risk	Safety Risk	Priority Ranking
Obstructed (Iced)	H	L	4
Dry chairs	H	L	4
Cracked/broken components	H	H	1
Voiding (ballast)	H	M	3
Out of adjustment	M	L	11
Contaminated (Leaves)	M	M	9
Plastic deformation/lipping	L	H	6
Wear	L	H	6
Loosed/missing (nuts)	L	M	12
Squat, RCF	L	H	6
Creep (switch)	M	M	9
Track gauge variation	M	H	2

According to Table 5, in order to undertake the required maintenance process, it is firstly necessary to identify the key factors and priority ranking that are required, to develop a reliable method for the risk-based maintenance of turnout systems. In this case, it is important to acknowledge the priority to perform periodic inspection and assurance reporting of critical assets (i.e. integrity of components). As a result, choice of materials and its design knowledge associated to maintenance practices are vital, in order to minimize any opportunity to experience the unknown unknowns.

5. Conclusions

This study assessed the risks and failure modes from the maintenance activities of special trackwork in railway industry; which are performed periodically to mitigate the deterioration of turnout geometry (track quality index) and the structural integrity of turnout components. There was a lack of studies on the maintenance priority and risk-based maintenance approach considering systems engineering for railway infrastructures. As a result, this study develops a new approach to consider risks and priority ranking for mitigation and restoration of turnout geometry to ensure that we can achieve and deliver:

- Safety of turnout operation
- Operational reliability of turnout systems
- Increased capacity
- Value for money through predictable and preventative maintenance approach
 - Technology to enable infrastructure-to-infrastructure and infrastructure-to-vehicle communications

The risk and vulnerability arising from the complex nature of turnout components and assets in various operational environments has thus been evaluated and highlighted in this paper. The insight into the risks and their potentials has led to the development of adaptive measures for the newly proposed risk-based maintenance model of turnout systems. Such methodology can be integrated into the design and preparation stages so that the turnout infrastructure resilience is built in, improving public safety and reliability.

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